

# VU Research Portal

## Why do people jump the way they do?

Bobbert, M.F.; van Soest, A.J.

### **published in**

Exercise and Sport Science Reviews  
2001

### **DOI (link to publisher)**

[10.1097/00003677-200107000-00002](https://doi.org/10.1097/00003677-200107000-00002)

### **document version**

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

### **citation for published version (APA)**

Bobbert, M. F., & van Soest, A. J. (2001). Why do people jump the way they do? *Exercise and Sport Science Reviews*, 29, 95-102. <https://doi.org/10.1097/00003677-200107000-00002>

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

### **Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

### **E-mail address:**

[vuresearchportal.ub@vu.nl](mailto:vuresearchportal.ub@vu.nl)

# Why Do People Jump the Way They Do?

Maarten F. Bobbert and A. J. "Knoek" van Soest

Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands

BOBBERT, M.F., and A.J. "KNOEK" VAN SOEST. Why do people jump the way they do? *Exerc. Sport Sci. Rev.*, Vol. 29, No. 3, pp 95–102, 2001. *When humans perform maximum height squat jumps, their segmental rotations contribute in a proximodistal sequence to the vertical acceleration of the center of gravity. The same kinematic pattern occurs in a forward dynamic model of the musculoskeletal system when muscle stimulation is optimized to maximize jump height. This paper examines why this kinematic pattern maximizes jump height in humans, given the design of the human musculoskeletal system.* **Keywords:** humans, coordination, ballistic movements, simulation, optimization

## INTRODUCTION

Movement patterns displayed by human subjects during various tasks have been described abundantly in the literature. It has often been reported that different subjects display similar, stereotyped, kinematics. This may be illustrated with the help of data on maximum height squat jumping, as collected in a previous study (2). In that study, markers were placed on the body as shown in Figure 1a to define four rigid body segments: feet, lower legs, upper legs, and head-arms-trunk (HAT). Figure 2a shows stick diagrams of one subject performing a squat jump, and Figure 3a shows the individual time histories of body segment angles of 21 subjects. The different subjects preferred different body configurations at the start of the jump. During the jump, however, the angle histories of the subjects converged to a common, stereotyped pattern.

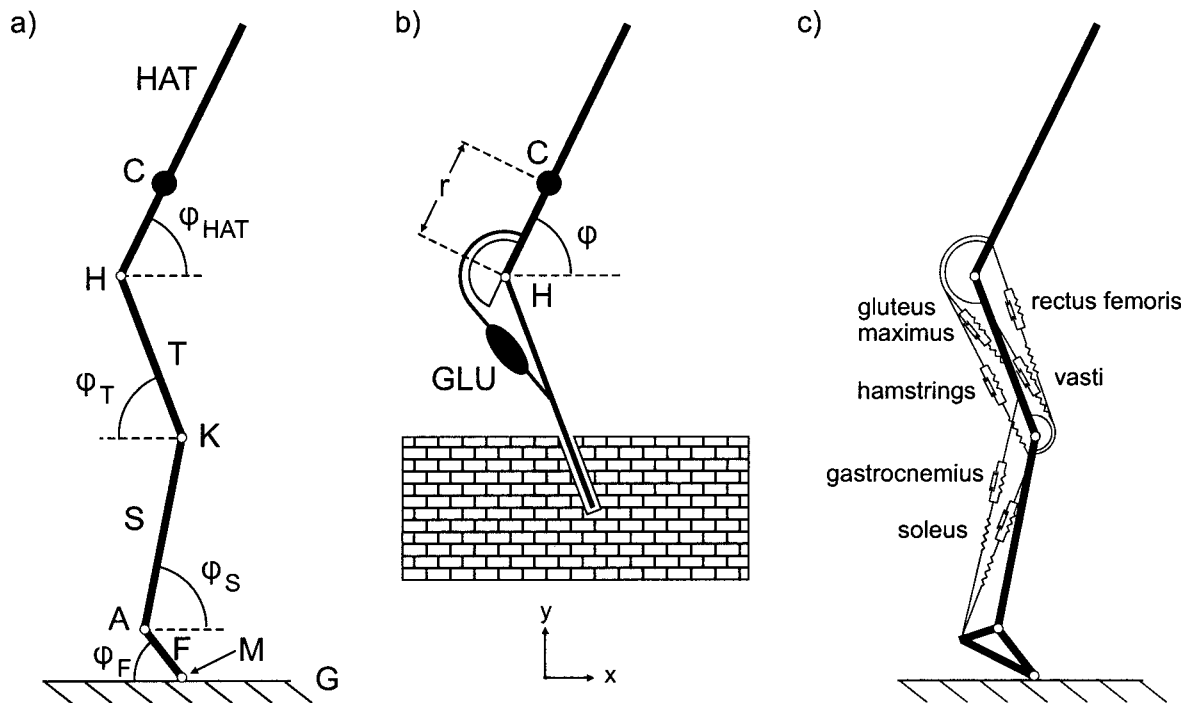
Why do different subjects display similar kinematic patterns? In a ballistic task such as vertical jumping, the maximally achievable performance is constrained by the properties of the musculoskeletal system. To what extent this maximum performance is approached ultimately depends on *coordination*, the generation of muscle stimulation patterns by the central nervous system. During practice, subjects may learn which stimulation pattern is optimal for their own

systems. Because different subjects have similar musculoskeletal system properties, their optimal solutions and the corresponding kinematic patterns also are likely to be similar. In passing, we note that some authors consider the observed stereotyped kinematic pattern to be different than the optimal pattern (3,4). For instance, it has been speculated (3) that subjects are trying to start the rotations of all segments simultaneously but that the inertial forces caused by trunk rotation initially force the knee and ankle joints into additional flexion, so that a proximodistal sequence ensues (see Figure 3a). In our view, the observed pattern of segmental rotations itself should be considered the optimal pattern; if subjects wanted to rotate the segments simultaneously, they would surely have learned the stimulation pattern required to realize it.

The assertion that the observed stereotyped kinematic pattern reflects the optimal solution to the task is reinforced when this pattern is compared with the optimal solution for a mathematical model of the musculoskeletal system. The model, which has been described in detail elsewhere (6), is shown schematically in Figure 1c. In short, the input of the model consists of the time histories of "stimulation" of Hill-type muscle models, and the resulting movement of the skeletal system is simulated by numerical integration. For this model, we first found muscle stimulation levels yielding equilibrium in the starting position (leftmost stick diagram in Figure 2b). Subsequently, we allowed the stimulation of each muscle to switch once to the maximum level ("bang-bang" control) and used a dynamic optimization technique to find the optimal combination of switching times (i.e., the combination that maximized the height reached by the center of mass [CM]). Figure 2b shows stick diagrams for the optimal solution, and Figure 3b (solid lines) shows segment angle time histories. Jump height, defined as height of CM at the

Address for correspondence: Maarten F. Bobbert, Institute for Fundamental and Clinical Human Movement Sciences, Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, the Netherlands (E-mail: m\_f\_bobbert@fbw.vu.nl).

Accepted for publication: January 19, 2001.



**Figure 1.** Models used in this study. (a) Definition of segment angles  $\phi$  of the feet (F), shanks (S), thighs (T), and HAT (with mass center C). In experiments, these segments were defined by markers placed on the fifth metatarsophalangeal joint (M), ankle (A), knee (K), hip (H), and neck. (b) Simple model in which only HAT can rotate, driven by a moment produced by the gluteus maximus (GLU). (c) Model of the musculoskeletal system used for forward dynamic simulations, composed of four body segments and six muscle-tendon complexes of the lower extremity, all represented by Hill-type muscle models.

apex of the jump relative to height of CM in upright standing, was 41 cm in the model, compared with  $44 \pm 5$  cm in the group of subjects. The close correspondence between experimental results and simulation results supports the view that subjects have indeed optimized their coordination with respect to jump height.

The purpose of this report is to understand why the pattern of segmental rotations found in jumping (Figure 3) is the optimal pattern, given the musculoskeletal system with which human beings are equipped. We first analyze the factors that determine jump height. Subsequently, we take a closer look at the movement pattern and discuss a previous hypothesis as to why this pattern could be optimal. Finally, the hypothesis is tested using simulations with the optimal control model of vertical jumping.

## VERTICAL JUMP HEIGHT IS DETERMINED BY MUSCLE WORK AND EFFICACY

What are the requirements of projecting CM to as great a height as possible? First, we need to realize that a subject can change the total mechanical energy of CM only by pushing against the ground. In the airborne phase, the subject is, by definition, no longer exerting force onto the ground, and the total energy of CM remains constant. The total energy of CM may be subdivided into potential energy, vertical kinetic energy (i.e., kinetic energy due to the vertical velocity of CM), and horizontal kinetic energy (i.e., kinetic energy due to the horizontal velocity of CM). In the airborne phase, vertical kinetic energy is transformed into potential energy

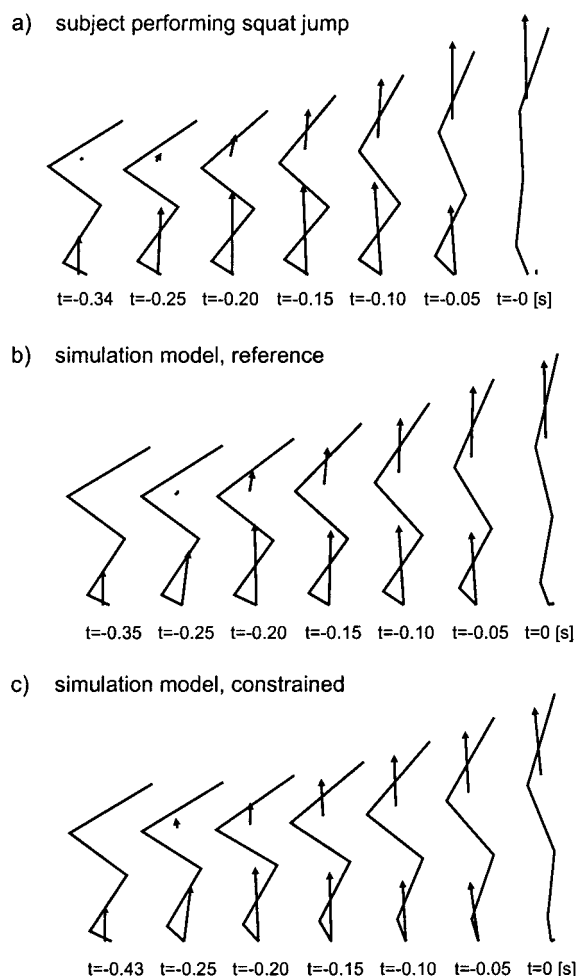
by the force of gravity. This means that to maximize jump height, we need to maximize the effective energy, i.e., the sum of potential energy and vertical kinetic energy of CM. During the push-off, the muscles perform mechanical work on the segments, thereby increasing the segmental energies, but only part of the segmental energies is transformed into effective energy. The remainder is converted into horizontal kinetic energy of CM, rotational energy of the segments, and energy due to the velocity of segmental mass centers relative to CM. The ratio of effective energy to total mechanical muscle work (total energy) will be called the *efficacy ratio*. The factors that determine the efficacy ratio and total work are addressed here.

## Factors That Determine the Efficacy Ratio

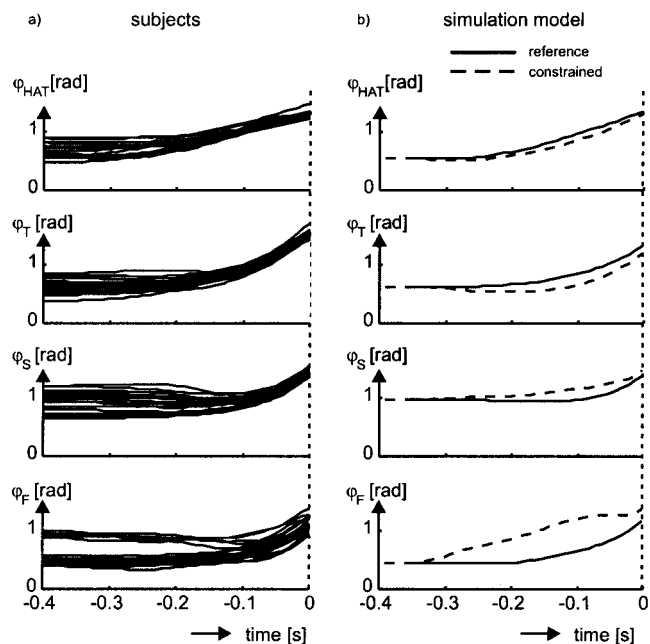
If we take our model of the human body (Figure 1c) and have a realistic amount of total energy at take-off available, how should we distribute the energy to maximize the efficacy ratio? Numerical optimization for efficacy shows that for the total energy of our model at take-off, a maximum efficacy ratio of 0.996 and a corresponding jump height of 51 cm are achieved when the three upper segments are oriented vertically with zero angular velocity and the feet are oriented horizontally and given a high rotational velocity. The optimality of this state is easily understood when we consider that maximizing effective energy is the same as minimizing useless energy. In the state described, there is no useless horizontal energy of CM. Moreover, the vertical velocity of CM is completely accounted for by the rotation of the feet, so that there is only useless energy in the shortest and lightest segments. In passing, we note that this high value of the

efficacy ratio depends critically on the smart construction of the body, with the heavy HAT segment located farthest from the point in contact with the ground. To confirm this, we turned the body upside down as a thought experiment. In that case, the maximum achievable value for the efficacy ratio was only 0.72.

The position of the system that maximizes the efficacy ratio, described earlier, is clearly different from the take-off positions observed in the subjects (Figures 2a and 3a) and the take-off position found in our simulation model performing a maximum height jump (Figures 2b and 3b). In the simulation, the actual efficacy ratio value was “only” 0.87. This is not unexpected, because in reality the efficacy ratio is not the sole determinant of jump height. To realize the ideal distribution of energy described above, the metabolic energy stored in the muscles should instan-



**Figure 2.** Stick diagrams of the push-off in maximum height squat jumping for a typical subject (a) and for optimal solutions of the simulation model (b and c). In each panel, the leftmost stick diagram depicts the position at the start of upward motion of the CM, the rightmost one depicts the configuration at the last frame before take-off, and the intermediate diagrams are spaced 50 ms in time, starting at the instant of take-off ( $t = 0$ ) and counting back in time. In each stick diagram, the ground reaction force vector is represented with its origin at the center of pressure, and the velocity vector of the CM is shown with its origin at the location of the CM. In the constrained optimization, it was required that the soleus was stimulated first and that the onset times of the other muscles were delayed by  $\geq 100$  ms.



**Figure 3.** (a) Segment angle histories (see definition in Figure 1a) measured in a study of 21 subjects performing vertical squat jumps (2). (b) Same variables as in panel a for optimal solutions for the simulation model, obtained in unconstrained and constrained optimization of muscle stimulation onset times using height reached by the CM as criterion. In the constrained optimization, it was demanded that soleus was stimulated first and that the onset times of the other muscles were delayed by  $\geq 100$  ms.

taneously be converted into mechanical energy and injected into the system. However, not all of the metabolic energy is present in the muscles actuating the feet. Moreover, muscles need to shorten to convert metabolic energy to work.

### Factors Determining the Work Produced by Muscles

The work produced by a muscle is the integral of the force of the muscle with respect to its shortening distance. Muscle force depends on contractile element length, velocity, active state (essentially the fraction of actin binding sites available for cross-bridge formation), and possibly the effects of contraction history on the properties of the contractile machinery. One of the fundamental muscle properties is that force decreases with shortening velocity; everything else remaining equal. Thus, to maximize the work produced by a fully activated muscle during a single contraction, its shortening distance should be made as large as possible and its shortening velocity as low as possible. If the muscle is not preactivated, active state should be built up as fast as possible during shortening. After all, if part of the shortening range is traveled at submaximal active state, the force is submaximal and so is the work produced. Because the building up of active state takes time (2), work production during shortening will benefit if this building up can be done during a preparatory countermovement. Finally, a muscle can be forcibly lengthened. When contractile elements lengthen while

producing force, work output is negative; the energy absorbed by the muscle is largely converted to heat.

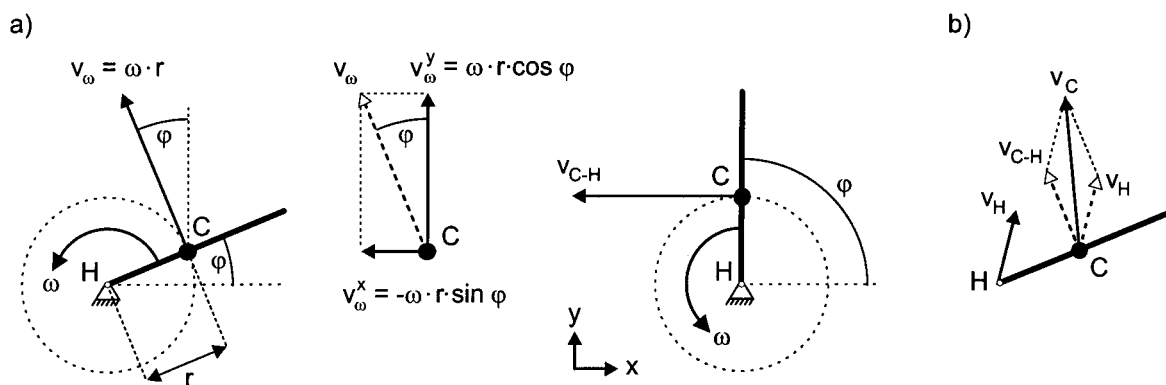
In jumping, the work of interest is the net work output of all muscles, with negative work partially offsetting positive work. What makes things complex is that contraction of one muscle has consequences for the motion of all body segments (7), and therefore for the length and contraction velocity of all other muscles. Another complication in vertical jumping is that the shortening range of muscles depends on the take-off position. It is explained later that achieving a take-off position in which the joints approximate full extension is a major challenge in jumping.

## A PROBLEM IN THE TRANSFORMATION OF ROTATION OF BODY SEGMENTS TO TRANSLATION OF CM

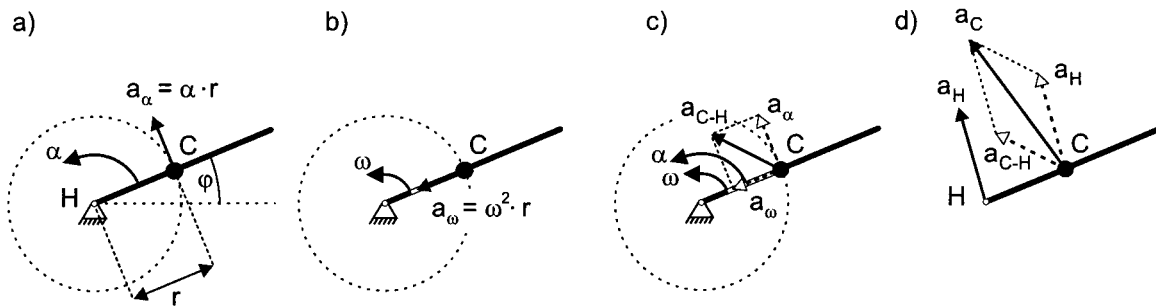
During the push-off in jumping, the linear velocity of CM is the variable of primary importance. However, the only way to generate such a linear velocity is to give the body segments an angular velocity. To come to an understanding of the geometrical problem that is inherent in the transformation from rotation of segments to translation of CM, let us begin by considering the kinematics of the HAT segment fixed at the hips (H) and rotating in the sagittal plane. If the segment has a constant angular velocity  $\omega$ , the mass center (C) has a linear velocity  $v_\omega$ , which is directed tangential to the circular path of C (Figure 4). This means that the vertical velocity of C depends on the angle  $\varphi$  of the segment with the horizontal. The transfer from  $\omega$  to vertical velocity is maximal when the segment is horizontal but zero when the segment is vertical (Figure 4). The change in the direction of the velocity of C is caused by the centripetal acceleration  $a_\omega$  (Figure 5). The segment may also have an angular acceleration  $\alpha$ , causing a tangential acceleration  $a_\alpha$  of C. If the segment has both an angular velocity and an angular acceleration, the linear acceleration of C is the sum of  $a_\omega$  and  $a_\alpha$  (Figure 5). In general, end point H will not be fixed and may have a linear velocity  $v_H$  and acceleration  $a_H$ . In that case, the linear velocity of C is the sum of  $v_H$  and  $v_\omega$  (Figure 4), and the linear acceleration of C is the vector sum of  $a_H$ ,  $a_\omega$ , and  $a_\alpha$  (Figure 5).

In jumping, we start from an equilibrium position, and we want to increase the vertical velocity of our CM by giving it a vertical acceleration. To do this, we activate our muscles. The resulting muscle forces cause angular accelerations of the segments, with contribution  $a_\alpha$  to the acceleration of CM (Figure 5). However, because of the angular accelerations, the angular velocities of the segments increase over time, and so does their contribution  $a_\omega$  to the acceleration of CM (Figure 5). As soon as the vertical components of  $a_\alpha$  (upward) and  $a_\omega$  (downward) sum up to the acceleration of gravity, take-off occurs. When we move slowly, we can easily stand up from a squatted position without losing contact with the ground, but in jumping,  $a_\omega$  increases so fast that we take off before our body segments have reached a vertical orientation. Let us first illustrate this, as was done elsewhere (1), by actuating the HAT segment fixed at H with a moment of gluteus maximus (Figure 1b). To maintain equilibrium in the starting angle  $\varphi$  (Figure 6), the moment is set to 147 Nm. When it is instantaneously increased to a fixed value of 400 Nm, HAT acquires a counterclockwise angular acceleration  $\alpha$  and C acquires a linear acceleration  $a_\alpha$ , with an upward component (Figure 6b). With the passage of time,  $\varphi$  increases and  $a_\alpha$  becomes directed more and more horizontally. Moreover, because of the gradual buildup of an angular velocity  $\omega$ , C acquires a centripetal acceleration  $a_\omega$ , the vertical component of which counteracts that of  $a_\alpha$ . The centripetal acceleration  $a_\omega$  grows with the square of  $\omega$  and becomes directed more and more downward as  $\varphi$  increases. Long before the segment is vertical, the situation is reached in which the sum of the vertical components of  $a_\alpha$  and  $a_\omega$  becomes equal to the acceleration due to gravity (Figure 6c). From here on, the ground would pull downward on H if H were fixed. If a pulling ground reaction force is impossible, as in the normal situation, the push-off would end at this instant and HAT would be airborne. The work produced by the gluteus moment up to this instant amounted to 312 J. Only 104 J of this work contributed to effective energy (corresponding to 19 cm of vertical displacement of C), so that the efficacy ratio was a meager 0.34.

The only way to prevent HAT from taking off at the given combination of  $\varphi$ ,  $\omega$ , and  $\alpha$  is to give H an upward vertical acceleration. If this is done throughout the push-off phase, it



**Figure 4.** (a) An angular velocity  $\omega$  of a segment causes a linear velocity  $v_\omega$  or  $v_{C-H}$  of the center of mass C relative to point H, directed tangential to the circular path of C about H. The linear velocity of C may be decomposed in a vertical and horizontal velocity. (b) If point H itself has a velocity  $v_H$ , the linear velocity of C is the vector sum of  $v_H$  and  $v_{C-H}$ .



**Figure 5.** (a) If a segment has only an angular acceleration  $\alpha$ , its center of mass C has a linear acceleration  $a_\alpha$  relative to point H, directed tangential to the circular path of C about H. (b) If the segment has only an angular velocity  $\omega$ , C has a centripetal linear acceleration  $a_\omega$ . (c) If the segment has both an angular acceleration and an angular velocity, the linear acceleration of C relative to H ( $a_{C-H}$ ) is the sum of  $a_\alpha$  and  $a_\omega$ . (d) If point H itself has an acceleration  $a_H$ , the linear acceleration of C is the vector sum of  $a_H$  and  $a_{C-H}$ .

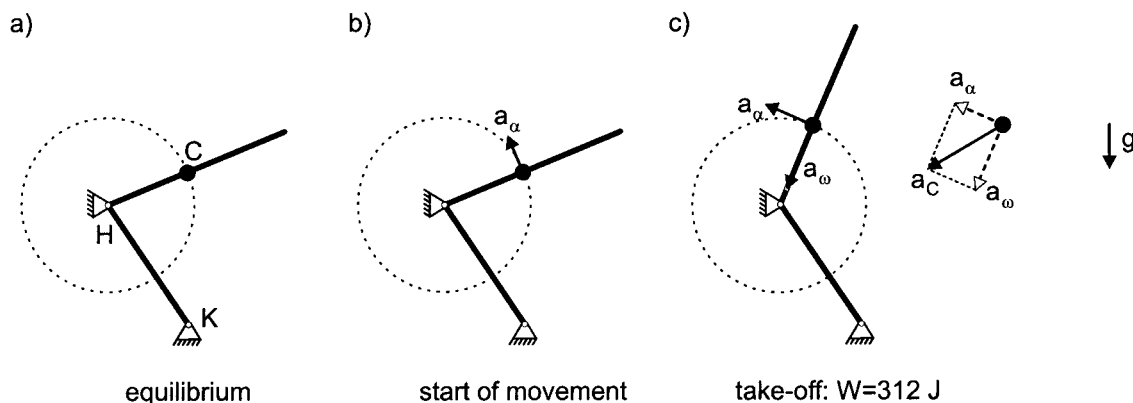
has an additional advantage: the resulting increase in the upward reaction force at the hips has a negative effect on  $a_\alpha$  and therefore results in a slowdown of the increase in  $\omega$  (Figure 7). To allow the system to generate an upward acceleration of H, however, it must be changed. The most simple change is to release H so that the gluteus moment actuates not only HAT but also the thighs. For simplicity, we have given the thighs zero mass, so that the mass center of the whole system remains at C. Again, the moment was 147 Nm in the equilibrium situation (Figure 8a) and increased to a fixed value of 400 Nm (Figure 8b). Components  $a_\alpha$  and  $a_\omega$  now reflect the linear accelerations of C caused by the two segments combined. When the moment had produced 312 J in this two-segment system, the acceleration of C was still upward (Figure 8c), and the system had already acquired 200 J of effective energy. The final performance of the gluteus moment was even better. At the instant of take-off (Figure 8d), it had produced 417 J. Of this 417 J, 219 J was converted to effective energy (corresponding to 40 cm of vertical displacement of C), so that the efficacy ratio was now 0.53. This shows that adding a light segment distal to HAT benefits both the work output and the efficacy ratio. Note, however, that of the last 104 J of extra work, only 19 J contributed to effective energy. Moreover, the condition for take-off in our two-segment system still occurred long before HAT was vertical (Figure 8d), due to the negative effect of  $a_\omega$ . A

take-off in this configuration, with flexed hip joints, is still premature, in that the potential for generation of muscle work is not fully exploited. Is there a way to further postpone take-off, resulting in a further increase in the effective energy?

#### HYPOTHESIS: THE SEGMENTAL ROTATION PATTERN HELPS TO PREVENT A PREMATURE TAKE-OFF

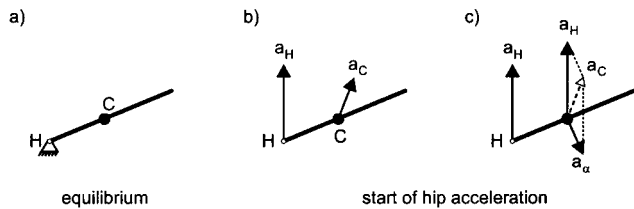
Above, we have seen that a two-segment jumping model driven by one muscle takes off prematurely in a configuration in which the joint between the segments is still flexed (Figure 8d). Human subjects, however, are able to achieve a take-off position in which the joints are almost fully extended (Figures 2a and 3a). How do they succeed in preventing a premature take-off?

Let us try to interpret what subjects do, with the help of Figure 9. The top diagram in this figure shows, for the 21 subjects from the previous study (2), time histories of the vertical velocity of CM determined from kinematic data. The faster the vertical velocity of CM increases, the greater is the upward acceleration, so the slope of each curve represents the vertical acceleration of CM. For each individual subject, the vertical acceleration of CM is more or less constant during the major part of the push-off.



**Figure 6.** (a) Results of a simulation with the model shown in Figure 1b. The top segment has a mass of 55.7 kg and a moment of inertia about its mass center C of 3.9 kg·m<sup>2</sup>. (a) In the equilibrium situation, a hip extensor moment of 147 Nm counteracts the moment due to gravity. (b) This hip extensor moment is instantaneously increased to a fixed value of 400 Nm. (c) The sum of the vertical components of  $a_\alpha$  and  $a_\omega$  is equal to the acceleration due to gravity, and the system is airborne.





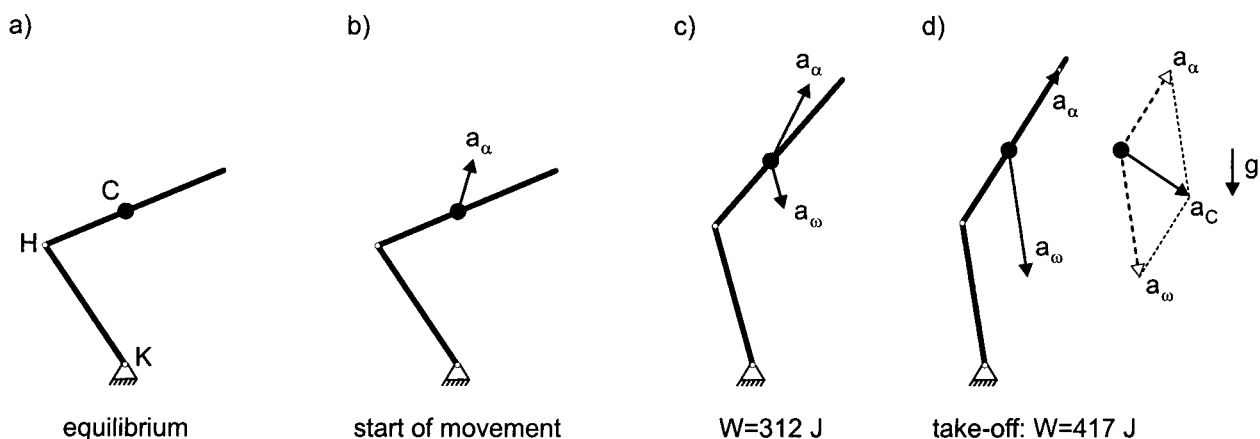
**Figure 7.** (a) Same situation as in Figure 6a. (b) If point H is accelerated upward, C acquires a linear acceleration. (c) The linear acceleration of C may be decomposed into the acceleration of H and a component  $a_\alpha$  related to a clockwise angular acceleration.

Shortly before take-off, at the instant that the curve reaches a peak value, the vertical acceleration becomes zero, and thereafter it becomes negative. Precisely at take-off, the slope is equal to the acceleration of gravity and the body is airborne.

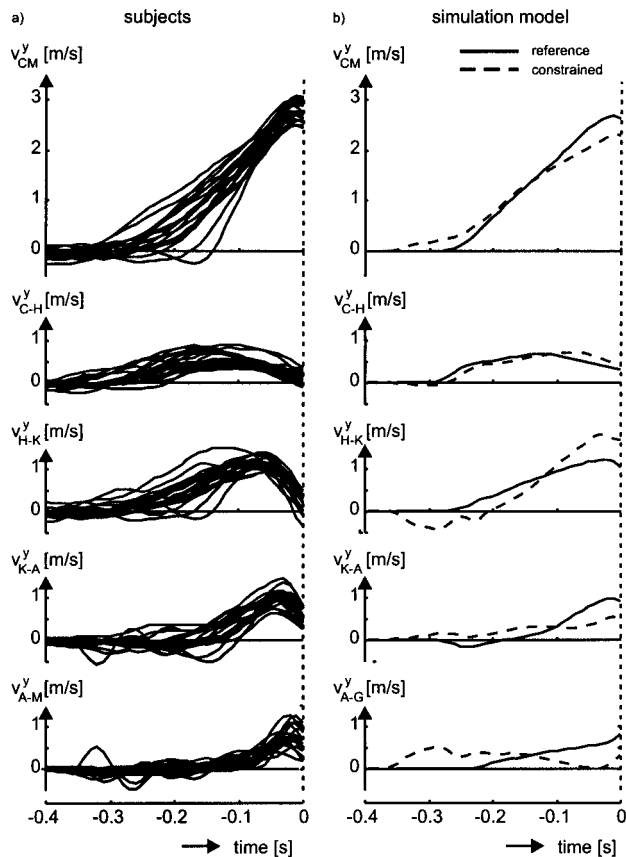
The vertical acceleration of CM results from segmental rotations, with the transfer being hampered by the geometric factor and the effect of the angular velocities discussed earlier (Figures 4 and 5). So let us now investigate the contributions of segmental rotations to the vertical acceleration of CM. For simplicity, we treat the system as if all mass is concentrated in HAT so that the CM of the whole system coincides with C. This allows us to decompose the vertical velocity of CM into four components: the vertical velocity of C relative to the hips, that of the hips relative to the knees, that of the knees relative to the ankles, and that of the ankles relative to the metatarsal heads. Figure 9a shows time histories of each of these components. The slope of a curve of a difference in vertical velocity between two points represents the difference in vertical acceleration between these points. The push-off is initiated by activation of the hip extensor muscles (2), causing an angular acceleration of HAT. Soon the corresponding vertical acceleration starts to drop (the vertical velocity difference between C and hips starts to level off). A premature take-off is prevented by a timely activation of the knee extensors and rotation of the thighs and shanks,

causing an upward acceleration of the hips. Thus, the hip extensor muscles can continue to shorten and contribute to effective energy. Somewhat later, the now familiar problem with the transfer from rotations to translations starts to limit the contributions of the rotations of thighs and shanks to the vertical acceleration of the hips. This occurs well before the knees are fully extended. A premature take-off can again be prevented, this time by activation of the plantar flexors. The resulting fast rotation of the feet causes an additional upward vertical acceleration of the ankles that, for a limited period of time, is able to keep the vertical acceleration of the hips so high that the acceleration of C remains above the acceleration of gravity. Finally, take-off is postponed further by rotation of the toes.

According to the argument just presented, the proximodistal sequence in muscle activation patterns and segmental rotations allows the system to achieve a take-off position in which the joints are extended as far as possible, so that the monoarticular hip extensors, knee extensors, and plantar flexors have had the opportunity to produce as much work as possible. Moreover, it helps to keep the efficacy ratio high. A key assumption in the argument is that if the distal segments were rotated first, they could no longer be used to accelerate the proximal segments upward, and thereby help to limit the increase in their angular velocity (as explained in Figure 7) and the associated increase in useless rotational energy. Although this is not the topic of the present report, it can be mentioned that the optimality of this proximodistal sequence of segmental rotations may well be related to several aspects of the design of our musculoskeletal system (1,5). For example, biarticular muscles such as rectus femoris and gastrocnemius allow proximal muscles to actuate distal segments, so that their work can be used more effectively. In addition, such a design contributes to a favorable mass distribution. Also, the long compliant tendons of plantar flexors can act like a catapult; by causing the shortening velocity of the muscle-tendon complex to be higher than that of



**Figure 8.** (a) Same situation as in Figure 6a, but this time H is not fixed, so that the hip extension moment actuates both the top segment and the bottom segment, which has zero mass and zero moment of inertia. (b) The moment is again increased from 147 to 400 Nm. (c) When 312 J has been produced, the center of mass still has an upward acceleration (compare with Figure 6c). (d) The sum of the vertical components of  $a_\alpha$  and  $a_\omega$ , which now represent the combined effect of the rotations of both segments, is equal to the acceleration due to gravity, and the system is airborne.



**Figure 9.** (a) Time histories of the vertical velocity of center of mass and vertical velocity differences between body landmarks (see Figure 1) measured in a study of 21 subjects performing vertical squat jumps (2). (b) Same variables as in panel a for jumps of the simulation model, obtained in unconstrained and constrained optimization of muscle stimulation onset times using the height reached by center of mass as criterion. In the constrained optimization, it was demanded that soleus was stimulated first and that the onset times of the other muscles were delayed by  $\geq 100$  ms.

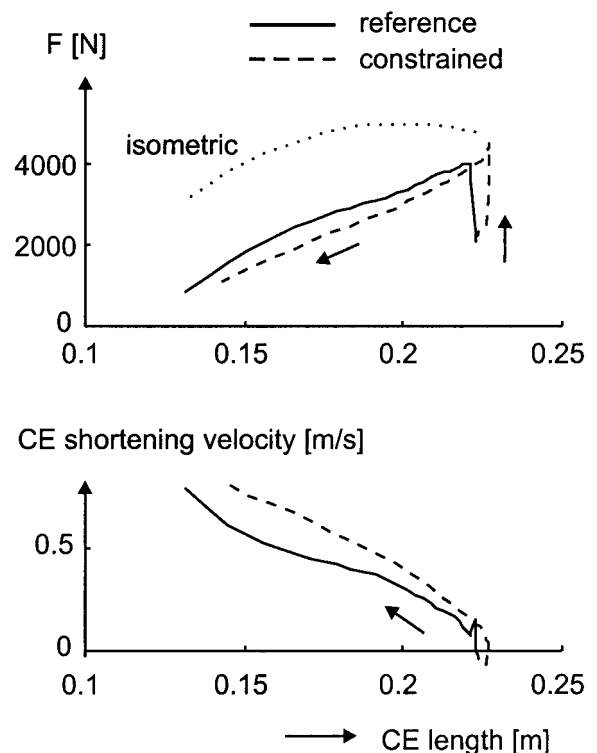
the muscle fibers, they allow for a fast rotation of the feet in the final part of the push-off.

## PUTTING THE HYPOTHESIS TO THE TEST

Based on the considerations presented here, it may be predicted that any tampering with the proximodistal sequence of segmental rotations leads to a premature take-off, causing a smaller shortening range and less work output of the hip and knee extensors, as well as a lower efficacy ratio. For obvious reasons, this prediction cannot be tested in experiments with human subjects. It can be tested, however, with the help of our optimal control model of the musculo-skeletal system (Figure 1c), which shows a segmental rotation pattern very similar to that of the subjects (Figures 2, 3, and 9). Let us use the model to investigate what happens when the pattern of segmental rotations is disturbed.

From our discussion of the factors that affect the efficacy ratio, it may be derived that a timely rotation of the feet is crucial in vertical jumping, because the feet are the most distal segment, with the smallest moments of inertia. To

achieve a premature rotation of the feet, we demanded that the push-off be initiated by stimulation onset of the soleus, and we optimized the stimulation onset times of the other muscles under the constraint that they occurred at least 100 ms after that of the soleus. Compared with the unconstrained optimization, jump height was reduced by 9 cm, the system now indeed took off with more flexed knee and hip joints (Figures 2c and 3b), total muscle work was 54 J less, and the efficacy ratio was reduced from 0.87 to 0.83. This means that  $\approx 30\%$  of the reduction in jump height was due to a reduction in the efficacy ratio and  $\approx 70\%$  was due to a reduction in total muscle work. The primary reason for the reduction in total muscle work turned out to be a reduction in the work output of the hip extensor muscles. Earlier, we pointed out that to maximize the work output of a fully activated muscle, its shortening distance should be made as large as possible, and because muscle force decreases with shortening velocity, its shortening velocity should be kept as low as possible. To identify whether it is a reduced range of shortening or an undesirably high contraction velocity that is responsible for the reduction in work output, we present in Figure 10 the force and shortening velocity of the glutei as a function of the contractile element length. The work produced is equal to the surface under the force-length curve. Clearly, the decrease in work in the constrained simulation was to a large extent due to a decreased force, caused by an increased



**Figure 10.** Force and shortening velocity of contractile elements (CE) of glutei plotted as function of length of CE, for the simulation model. The parabola labeled "isometric" represents the force that can be produced at maximum active state and zero shortening velocity. In the reference simulation, muscle stimulation onset times were optimized using height reached by the center of mass as criterion. In the constrained optimization, it was required that the stimulation onset of soleus occurred first and that the onset times of the other muscles were delayed by  $\geq 100$  ms. Arrows indicate the direction of time.



shortening velocity. This finding indicates that part of the challenge in jumping is to strike a compromise between minimizing the angular velocities of segments to keep the shortening velocities of the muscles low and maximizing them to maximize the vertical velocity of CM. The compromise is found in a balanced contribution of segmental rotations to the vertical velocity of CM.

## SUMMARY AND CONCLUSION

In vertical jumping, segmental rotations contribute in a proximodistal sequence to the vertical acceleration of CM. Given the design of the human musculoskeletal system, this sequence serves three functions. First, it helps to restrain the angular velocities of the proximal segments and thereby helps to restrain their negative effect on the vertical acceleration of CM. This prevents a take-off position in which the muscles have not been able to produce work over their full shortening range. Second, it ensures a balanced contribution of segmental angular velocities to the vertical velocity of CM. This is required to prevent the shortening velocities of some muscles from becoming disproportionately high, so that their contribution to force and work production is hampered. Finally, the restraining effect on the angular velocities of the heavy

proximal segments helps to maximize the efficacy of the work produced.

## Acknowledgments

We would like to thank Richard Casius for assistance with the simulations and Han Houdijk for the stimulating discussions on the similarities and differences between jumping and speed skating.

## References

1. Bobbert, M.F., and G.J. van Ingen Schenau. Coordination in vertical jumping. *J. Biomech.* 21:249–262, 1988.
2. Bobbert, M.F., and J.P. van Zandwijk. Dynamics of force and muscle stimulation in human vertical jumping. *Med. Sci. Sports Exerc.* 31:303–310, 1999.
3. Hopper, B.J. *The Mechanics of Human Movement*. London: Granada Publishing, 1973, p.146–147.
4. Hudson, J.L. Coordination of segments in the vertical jump. *Med. Sci. Sports Exerc.* 18:242–251, 1986.
5. van Ingen Schenau, G.J. From rotation to translation—constraints on multi-joint movements and the unique action of bi-articular muscles. *Hum. Mov. Sci.* 8:301–337, 1989.
6. van Soest, A.J., A.L. Schwab, M.F. Bobbert, and G.J. van Ingen Schenau. The influence of the biarticularity of the gastrocnemius muscle on vertical-jumping achievement. *J. Biomech.* 26:1–8, 1993.
7. Zajac, F.E. Muscle coordination of movement: a perspective. *J. Biomech.* 26:109–124, 1993.